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Advancing Enhanced Geothermal Reservoirs with Ionic Liquids as Potential Geothermal Fluid

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Enhanced Geothermal System (EGS), Ionic liquids (ILs), Hydraulic conductivity

ABSTRACT

Enhanced Geothermal System (EGS) is a type of geothermal energy system that involves creating a fracture system in the Earth's subsurface to extract heat, allowing for water or other fluids to be injected through designated wells. As a result of its desirable properties and availability, water remains the predominant geothermal fluid of choice. Nonetheless, water is prone to exhibiting breakthrough phenomena, as it travels from an injection well to a production well through large, highly-permeable fractures that offer minimal resistance to hydraulic and frictional forces. The main drawback associated with high-conductivity pathways is the corresponding reduction in heat extraction efficiency over time, as a consequence of the progressive cooling of the bulk rock matrix. To ensure the long-term sustainability of enhanced geothermal systems, enhancing the hydraulic characteristics of the geothermal fluid is imperative. One potential option for improving the hydraulic properties of the geothermal fluid is through the use of ionic liquids (ILs). The most pertinent characteristics of ILs that render them favorable for improving the hydraulic conductivity within fractures of an EGS are their viscosity, thermal stability, and ability to maintain in a liquid state. In this paper, two pyridine-based ionic liquids were synthesized and characterized using H-NMR and HPHT viscosity measurements. The HPHT viscosity analysis involved applying pressures of up to 1800 psi and temperatures of up to 480 °F to the ionic liquids. The results suggest that these ILs tend to flow more readily through smaller fracture systems with higher temperatures, rather than the larger ones with lower temperatures. This flow diversion is a gradual equilibrium process as the temperature in larger fractures starts decreasing over an extended period. The results of this study contribute to the growing body of research on geothermal energy and offer new avenues for further exploration and development of sustainable energy sources.

1. Introduction

Geothermal energy is a sustainable energy resource that utilizes heat from the earth's crust, offering a clean and reliable alternative to traditional fossil fuels. Geothermal wells are drilled deep into the earth's crust to extract energy, by harnessing the heat from these natural sources. The utilization of the geothermal resource depends on the reservoir temperature, where low temperature reservoirs are used for direct heating and cooling, and high temperature reservoirs are used for electricity generation.

Enhanced Geothermal Systems (EGSs) consist of deep engineered reservoirs having high temperatures with insufficient permeability and low fluid saturation (Figure 1). Hydraulic fracturing is employed in EGSs to enhance the reservoir permeability and harvest the heat by circulating working fluid, typically water, to extract the heat from the reservoirs. The concept of EGS emerged in the 1970s at the Fenton Hill project, conducted at the Los Alamos National Laboratory in the United States (Tenzer, 2001).

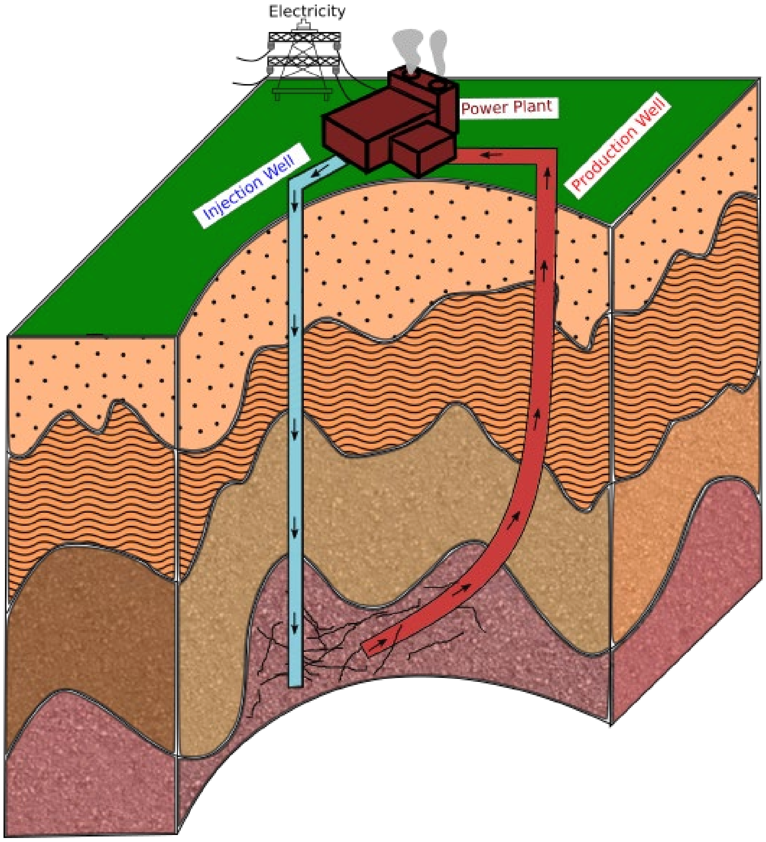

Figure 1: Schematics of an enhanced geothermal system.

One of the critical long-term issues in EGS reservoirs is managing the fluid flow through the reservoir to achieve optimal heat transfer performance. Due to the heterogeneous nature of fractures, fractures with higher hydraulic conductivity will take more fluid flow than others. This could potentially lead to limited heat extraction from only a small portion of the reservoir, which causes a rapid thermal decline of the heat extraction. This phenomenon is similar to water breakthrough in oil and gas reservoirs when the injected water finds few fast paths to the production well.

The temperature of the bounding rock matrix is depleted faster near fractures with higher hydraulic conductivity compared to the reservoir with lower permeability fractures. As the rock matrix cools down, the fracture widens due to thermal contraction and leads more fluid to flow through the path(s) with insufficient heat energy. For a given fluid velocity, due to the higher shear rate, pressure loss through fractures with low hydraulic conductivity is higher than fractures with higher hydraulic conductivity. That means fluid will travel at a lower velocity in the fractures with lower permeability to reach a pressure differential equilibrium with fractures with higher hydraulic conductivity. Another challenge in EGS is mineral dissolution, which has a negative impact on fracture permeability. These challenges limit the efficiency of heat extraction from the stimulated reservoir volume.

Geothermal working fluids play a significant role in geothermal energy extraction. Water is commonly used as a working fluid, however, different fluids such as supercritical carbon dioxide (ScCO2) have been proposed as an alternative fluid (Brown, 2000; Isaka et al., 2019). While using CO2 as a working fluid aid in CO2 storage, CO2 has a lower heat capacity and thermal conductivity than other common geothermal fluids specifically water, which can limit its ability to efficiently transfer heat.

Ionic liquids (ILs) are a group of molten salts known for their remarkable features such as low melting points (typically below 220 °F) and negligible vapor pressure which sets them apart from traditional solvents (Baker et al., 2005). Ionic liquids have unique characteristics that make them a potential option for use in thermal energy storage technologies. These properties include high heat capacity, low volatility, and high chemical stability. As a result, they have the potential to be effective working fluids for thermal energy storage systems. Ionic liquids have gained attention as potential working fluids in geothermal systems due to their unique properties. They offer several advantages over traditional working fluids, including high thermal stability, low toxicity, and tunable properties. Ionic liquids hold promise in addressing fluid flow through the fast path, i.e., short-circuiting. Ionic liquids have the unique ability to change their rheological behavior in response to variations in shear rates and temperatures. By leveraging this characteristic, ionic liquids can be designed to control the flow distribution within the geothermal reservoir. These advantages could make them a promising solution for enhancing the efficiency and sustainability of geothermal energy production.

In this study, two ionic liquids were synthesized and characterized using H-NMR. The rheological properties of the synthesized ionic liquids were measured at different temperatures and pressures adhering to geothermal reservoir conditions, where a rheological model was obtained for each test condition. Theoretical pressure drop investigation in rectangular fracture was performed using the measured ionic liquid rheology, which was compared to water to investigate the potential benefits.

2. Methodology

2.1 Ionic Liquid Development

Considering the geothermal application environment, two ionic liquids having the characteristics required for high-pressure and high temperature applications were synthesized for this investigation. The first ionic liquid, N-hexylpyridinium bromide (HPyBr), was synthesized by adding 1-bromohexane (0.5 mol, 90 gr) to pyridine (0.5 mol, 39.55 gr) with a 10% excess in a flat-bottom flask. The mixture is stirred at 149 °F for 24 hours, resulting in the formation of 1-hexylpyridinium bromide.

The resulting HPyBr is used as a precursor for synthesizing the N-hexylpyridinium tetrafluoroborate (HPyBF4). The HPyBF4 was synthesized by adding the 1-hexylpyridinium bromide and sodium tetrafluoroborate (NaBF4) (0.5 mol, 60.38 gr) and 80 mL of water with a 10% excess of sodium tetrafluoroborate in a flat-bottom flask. The solutions of sodium tetrafluoroborate and water were slowly added to the N-hexylpyridinium bromide and mixed for 24 hours. After allowing the solution to sit for 24 hours, the N-hexylpyridinium tetrafluoroborate was extracted from the water solution. The remaining components, including water and 1-bromohexane, were then extracted through vacuum-drying. The sodium bromide and sodium tetrafluoroborate were filtered to obtain N-hexylpyridinium tetrafluoroborate.

2.2 Ionic Liquid Characterization

Proton nuclear magnetic resonance (1H NMR) was used to verify the synthetization of ionic liquids. H-NMR is a technique that utilizes nuclear magnetic resonance in spectroscopy to analyze the hydrogen-1 nuclei present in a substance's molecules. Its primary purpose is to deduce the molecular structure based on the obtained NMR spectra. Bruker NMR, Ascend 400 was used to perform H-NMR on the synthesized IL samples. Figure 2 shows the apparatus while measuring the proton spectrum for an IL sample dissolved in chloroform-d (CDCl3).

Figure 2: Bruker NMR, Ascend 400, used to characterize the ionic liquids.

2.2 Rheology measurement

Chandler HPHT viscometer Model 5550 (Figure 3) was utilized to measure the rheological properties of the developed ionic liquids. The viscometer follows the rotor and bob geometry specified by ISO and API standards, which are designed for measuring fluid viscosity under high-pressure and high-temperature conditions. The equipment consists of a sliding carbon dry-block heater and a digital torque sensor positioned outside the sample cell. The rotor drive system incorporates a speed control mechanism to regulate the shear rate, while torque measurements are performed by a sensor located outside the sample cell. Pressure is applied to the fluid sample, around 55 cc, using nitrogen gas.

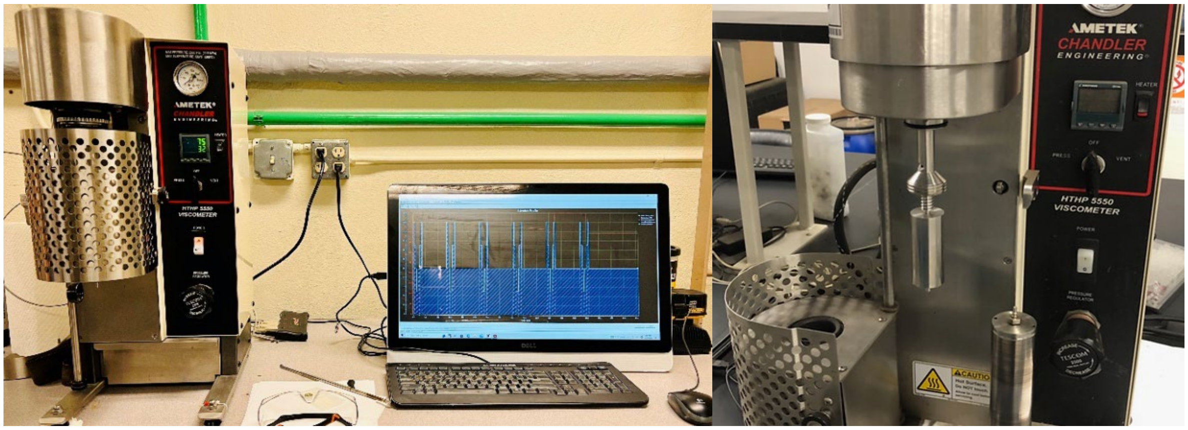

Figure 3: Rheology measurement using Chandler HPHT 5550 viscometer.

The HPHT viscometer measures viscosity, sample temperature, pressure, and shear rate at 1 hertz. A sample of the raw data for HPyBF4 at a constant pressure of 100 psi is illustrated in Figure 4, which shows viscosity, temperature, pressure, and shear rate versus time. The rheology data were average at each tested temperature, pressure, and shear rate for the analysis.

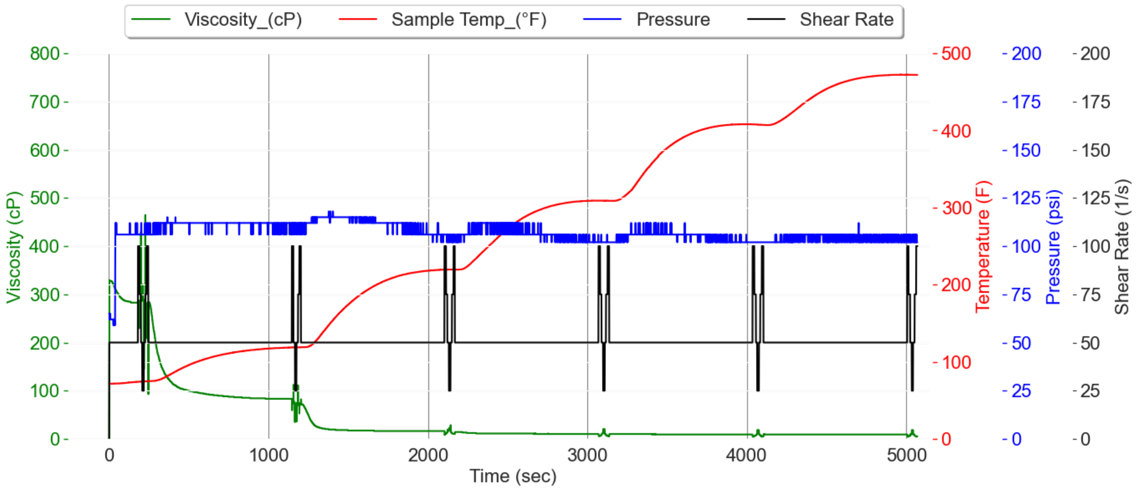

Figure 4: Rheology measurement at constant pressure for HPyBF4.

3. Results and Discussion

3.1 Ionic Liquid Characterization

To verify the structure of the synthesized ionic liquids, H-NMR testing was performed. Figure 5a-b presents the H-NMR characterization of HPyBr and HPyBF4, respectively. Although most of the hydrogen atoms were successfully identified and assigned based on the H-NMR analysis for HPyBr, as evidenced by the presence of green peaks, there were specific hydrogen atoms depicted in yellow color, indicating that H-NMR was unable to detect or assign them. In the NMR plots, the peaks are representative of the number of different neighborhoods and the area under the peaks is representative of the number of atoms at the specific neighborhoods. In this case, there are 4 hydrogen atoms in one neighborhood while the area under the corresponding curves are showing around 3 atoms.

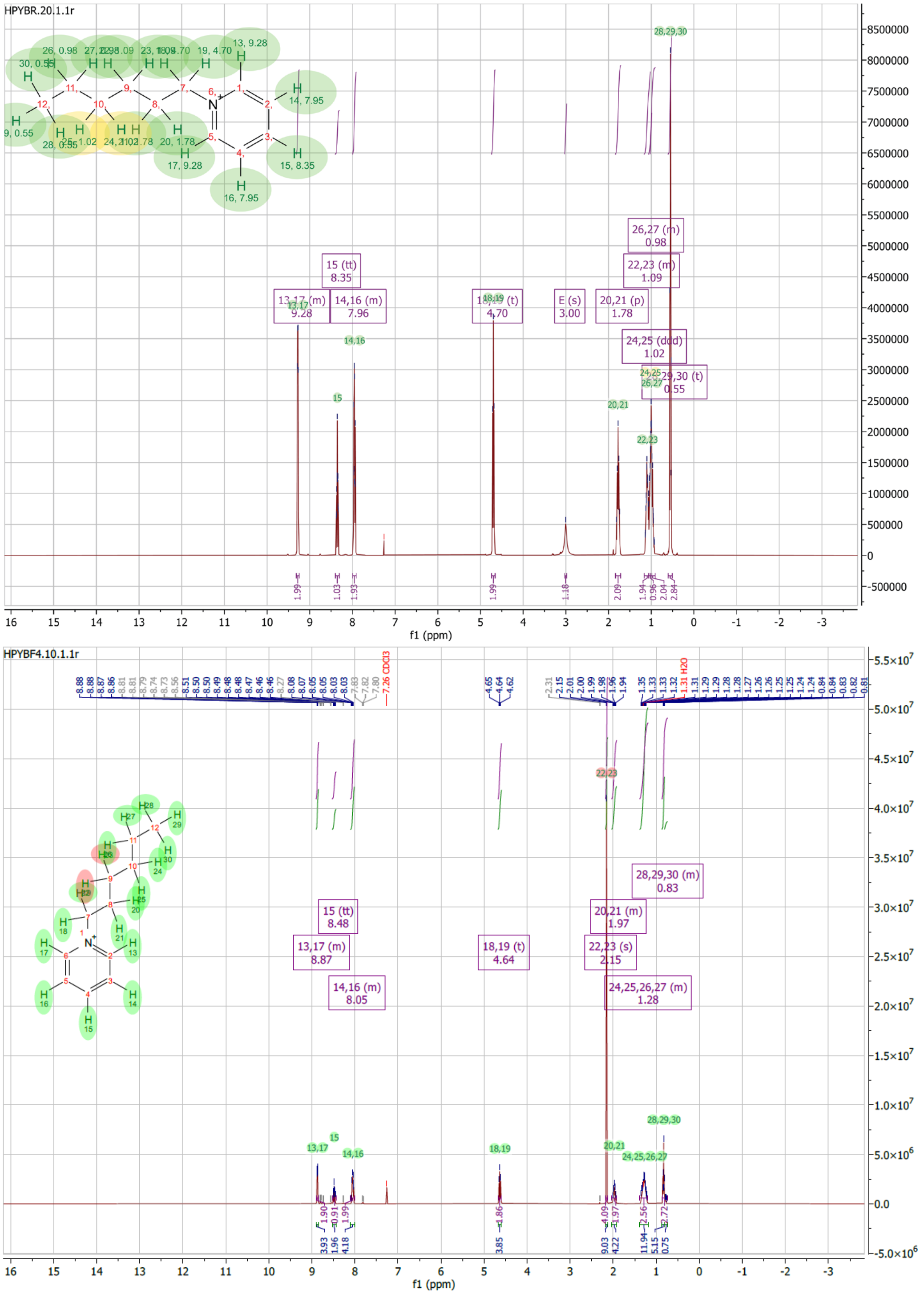

Figure 5: H-NMR spectrum of in chloroform-d solution showing characteristic proton signals of (a) HPyBr, and (b) HPyBF4.

The characterization of HPyBF4 using H-NMR is shown in Figure 5b. While the majority of the hydrogen atoms were successfully identified and assigned using H-NMR, as indicated by the presence of green peaks, there were some hydrogen atoms indicated in red color which suggest that H-NMR was unable to identify them.

The synthesis of HPyBF4 is a two-step process and it has been observed that the yield is low. Additionally, purifying the final product poses challenges, which can introduce impurities into the sample. These impurities can lead to the H-NMR characterization not recognizing all hydrogen atoms.

3.2 Rheology

3.2.1 Constant pressure rheology

The rheological behavior of HPyBF4 and HPyBr was investigated under a constant pressure of 100 psi. The relationship between shear rate and shear stress was examined at different temperatures and shear rates. Figure 6 presents the rheological properties of HPyBF4 and HPyBr, showcasing the results obtained. In Figure 6(a), the relationship between shear rate and shear stress for HPyBF4 is depicted at various temperatures. On the other hand, Figure 6(b) demonstrates the viscosity of HPyBF4 plotted against temperature for different shear rates. For HPyBr, Figure 6(c) showcases the shear rate versus shear stress at different temperatures, providing insights into its rheological behavior. Figure 6(d) presents the viscosity versus temperature for HPyBr at various shear rates.

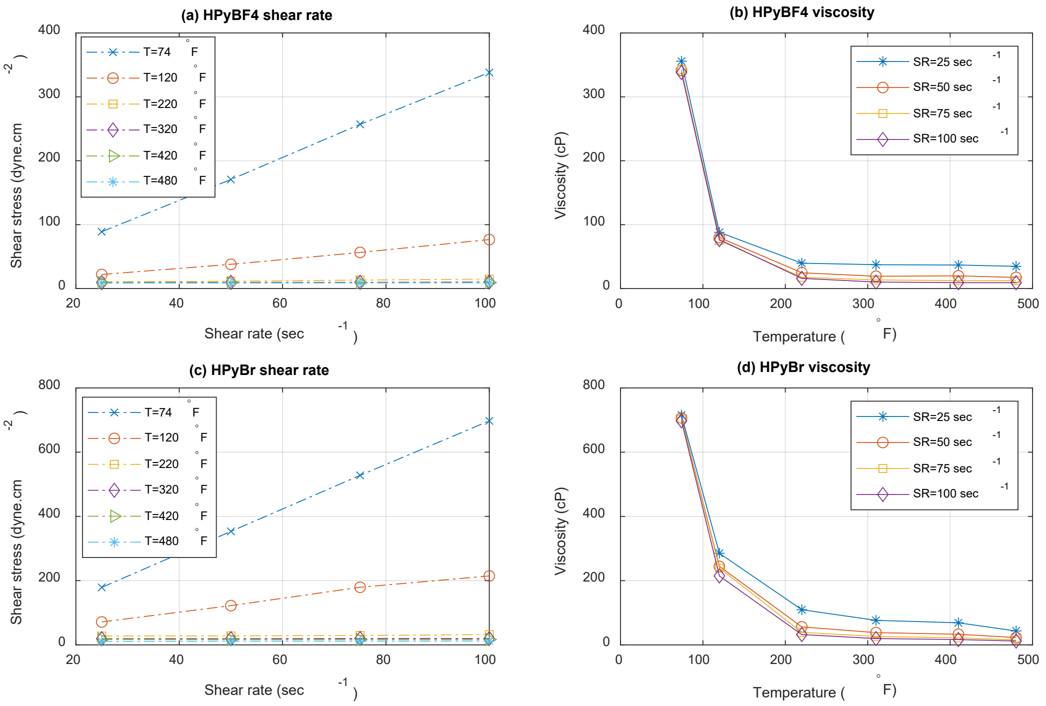

Figure 6: Shear stress and viscosity behavior at 100 psi constant pressure for (a) HPyBF4 at varying shear rate, (b) HPyBF4 at varying temperature, (c) HPyBr at varying shear rate, and (d) HPyBr at varying temperature.

The influence of temperature on viscosity behavior can be observed in Figure 6. In the case of HPyBF4, increasing temperature leads to a decrease in shear stress and viscosity. However, for temperatures higher than 310 °F, a slight decrease in shear stress and viscosity can be seen (Figure 6a-b). Similar trends can be observed for HPyBr concerning temperature (Figure 6c-d), but HPyBr exhibits higher shear stress and viscosity compared to HPyBF4.

To facilitate a better comparison between the two ionic liquids (ILs), a power law model, $\tau = k\,\gamma^n$, which describes the shear behavior at different temperatures, was fitted to the experimental data. The resulting constants, *n* and *k*, for each IL at various temperatures, are provided in Table 1. The table also includes the coefficient of determination (r^2) for each model fit, indicating the goodness of fit for the power law model to the data.

Table 1. Shear stress versus shear rate power law model constants of HPyBF4 and HPyBr at a constant pressure of 100 psi.

Ionic Liquid	Temperature (°F)	*n*	*k*	r^2
HPyBF4	74	0.972	3.848	1
	120	0.952	0.943	1
	220	0.262	4.34	0.94
	310	0.059	7.668	0.85
	410	0	9.186	0.01
	480	0.038	7.623	0.69
HPyBr	74	0.981	7.631	1
	120	0.799	5.497	1
	220	0.109	18.798	0.78
	310	0.027	17.406	0.74
	410	-0.031	18.875	0.76
	480	0.063	8.866	0.92

For HPyBF4, Table 1 reveals that as the temperature increases, the value of the parameter *n* decreases. This indicates a deviation from purely Newtonian behavior, suggesting that the viscosity of HPyBF4 is not solely dependent on shear rate but also on other factors. The parameter *k* also exhibits variations with temperature, indicating different flow properties at different temperatures. In general, the r^2 values indicate a good fit for the power law model, except for the test at 410 °F where the relationship between shear stress and the shear rate appears weaker, possibly due to the influence of elevated temperatures.

Similarly, for HPyBr, the parameter *n* decreases as the temperature increases, indicating non-Newtonian behavior. This suggests that the viscosity of HPyBr is also affected by factors other than shear rate. The parameter *k* also shows variations with temperature, and the r^2 values generally indicate a good fit for the models.

The decreasing values of the n parameter with increasing temperature for both HPyBF4 and HPyBr suggest non-Newtonian behavior. Non-Newtonian fluids do not follow a linear relationship between shear stress and shear rate, as observed in Newtonian fluids. The decreasing trend indicates that the viscosity of the ionic liquids decreases as the shear rate increases. This behavior is often observed in complex fluids where factors such as molecular structure, interactions, and particle or polymer content influence the flow characteristics.

Comparing the parameters and their values between HPyBF4 and HPyBr, it is clear that each ionic liquid exhibits its unique shear behavior. The differences in the *n* and *k* values indicate variations in their flow properties. HPyBF4 generally demonstrates lower consistency with lower *k* values, while still displaying a pronounced shear-thinning behavior compared to HPyBr. The term consistency refers to a material's ability to withstand flow or deformation when subjected to applied stress, reflecting its capacity to maintain structure and resist flow under external forces. Conversely, HPyBr exhibits higher consistency with higher *k* values.

Figure 7 presents a comparative analysis between HPyBF4 and HPyBr under varying temperatures and shear rates. The comparison is performed at two specific temperatures: 74 °F and 480 °F (depicted in Figures 7a and 7c, respectively), as well as two different shear rates: 25 sec^{-1} and 100 sec^{-1} (illustrated in Figures 7b and 7d, respectively). Notably, it should be emphasized that the pressure is consistently maintained at 100 psi throughout the entire comparison.

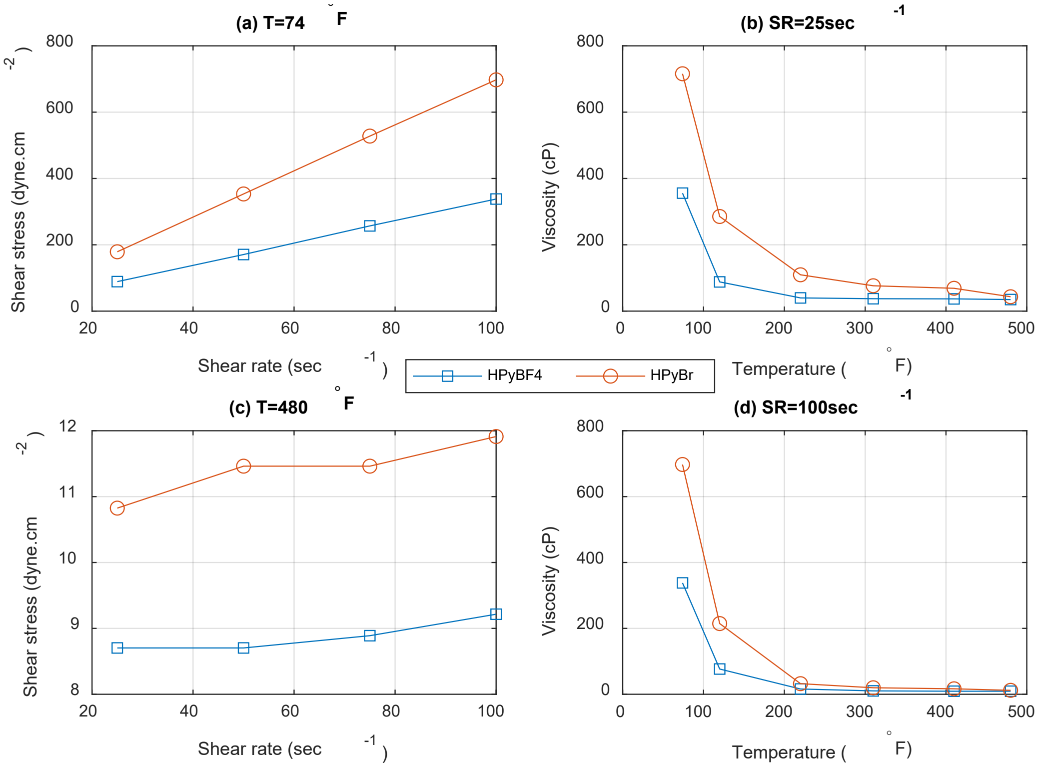

Figure 7: Constant pressure comparison of HPyBF4 and HPyBr at (a) 74 °F, (b) 25 sec^{-1}, (c) 480 °F, and (d) 25 sec^{-1}.

HPyBF4 exhibits lower shear stress and viscosity values compared to HPyBr. The dissimilarities in shear stress and viscosity can be attributed to the distinctive molecular structures and chemical compositions of the two substances. The higher shear stress and viscosity observed in HPyBr indicate that its molecular structure promotes stronger intermolecular interactions and greater resistance to flow. This could be due to factors such as more molecular structures, increased molecular polarity, larger molecule size, or stronger ionic interactions within the liquid.

On the other hand, HPyBF4 demonstrates lower shear stress and viscosity values, suggesting that its molecular structure allows for easier flow and reduced intermolecular interactions. This could be attributed to weaker ionic interactions within HPyBF4 compared to HPyBr. The structural disparities among the ionic liquids lead to variations in their physical properties, including viscosity and shear stress response, as these properties directly depend on intermolecular forces and molecular mobility.

To gain a deeper understanding of the observed trends, factors such as molecular size, shape, polarity, as well as the strength and nature of the interactions within the liquid, need to be considered. These factors collectively contribute to the variations in physical properties exhibited by the two ionic liquids.

3.2.2 Constant temperature rheology

Figure 8 depicts the viscosity characteristics of HPyBF4 and HPyBr at a constant temperature of 380 °F while subject to varying shear rates and pressures. Figures 8a and 8b illustrate the viscosity behavior of HPyBF4 under different shear rates and pressures. The impact of shear rate and pressure on viscosity is relatively minimal at 380 °F. A similar trend is observed for HPyBr, as depicted in Figures 8c and 8d. The findings suggest that pressure does not exert a substantial influence on the viscosity of both HPyBF4 and HPyBr. Despite variations in shear rate and pressure, the viscosity of the fluids remains relatively stable at the given temperature of 380 °F.

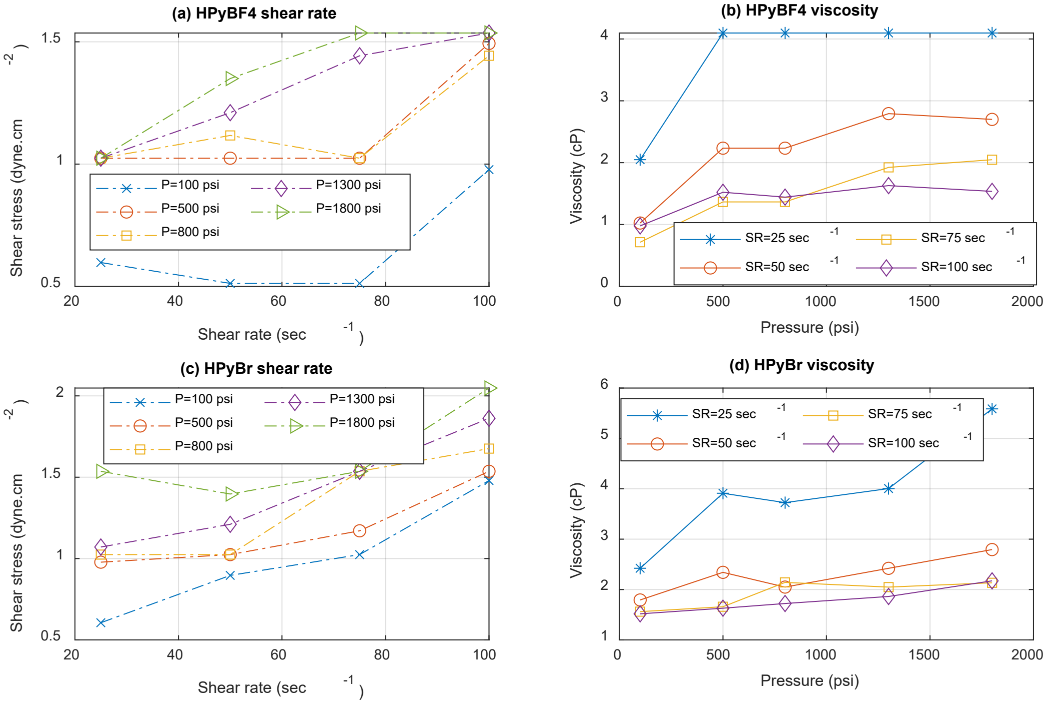

Figure 8: Viscosity behavior at 380 °F: (a) HPyBF4 at varying shear rates, (b) HPyBF4 at varying pressure, (c) HPyBr at varying shear rates, and (d) HPyBr at varying pressure.

In line with the analysis conducted for varying temperatures, a power law model was utilized to establish the relationship between shear stress and shear rate for the HPyBF4 and HPyBr tests conducted under varying pressure conditions. The resultant *n* and *k* constants, along with the coefficient of determination r^2, are presented in Table 2.

Table 2. Shear stress versus shear rate power law model constants of HPyBF4 and HPyBr at 380 °F.

Ionic Liquid	Pressure (psi)	*n*	*k*	r^2
HPyBF4	100	0.382	0.137	0.33
	500	0.255	0.406	0.47
	800	0.208	0.497	0.47
	1300	0.306	0.377	0.98
	1800	0.291	0.418	0.93
HPyBr	100	0.661	0.067	0.93
	500	0.341	0.295	0.77
	800	0.429	0.23	0.83
	1300	0.435	0.242	0.92
	1800	0.203	0.718	0.41

The rheological behavior of HPyBF4 and HPyBr was analyzed using the power law model under different pressure conditions. HPyBF4 displayed shear-thinning behavior with power law exponent *n* values ranging from 0.208 to 0.382, indicating decreased viscosity as the shear rate increased. The flow behavior index *k* values ranged from 0.137 to 0.497, indicating consistent flow properties. HPyBr also exhibited shear-thinning behavior with power law *n* exponent values ranging from 0.203 to 0.661, indicating viscosity reduction at higher shear rates. The flow behavior index *k* values ranged from 0.067 to 0.718, indicating consistency in flow behavior. Both liquids showed slight variations in the parameters with respect to pressure, suggesting a minor influence of pressure on their flow behavior.

Based on the results, it can be concluded that at a constant temperature of 380 °F, both HPyBF4 and HPyBr show a weak pressure dependency in their shear behavior. The small variations in the power law constants at various pressure levels indicate that the effect of pressure on flow behavior is negligible. Additionally, shear-thinning behavior is seen in both ionic liquids, with HPyBr typically exhibiting a milder shear-thinning tendency with an average power law *n* constant of 0.41 compare to the HPyBF4 with an average of 0.28.

Figure 9 compares HPyBF4 with HPyBr over a range of shear rates (Figure 9 a, c) and pressures (Figure 9 b, d) at a constant temperature of 380 °F. According to the results, the viscosity slightly increases as pressure rises. Both ionic liquids have viscosities that change from around 2 cP to almost 6 cP. The operating temperature of 380 °F can be responsible for the low viscosity values in the range of 1 to 6 cP. The influence of pressure on viscosity appears to be insignificant, likely due to the high temperature of 380 °F, which contributes to the exceptionally low viscosity of the ionic liquids. The reduced sensitivity of viscosity to pressure at 380 °F may be due to the thermal energy overriding the pressure-induced effects on molecular interactions.

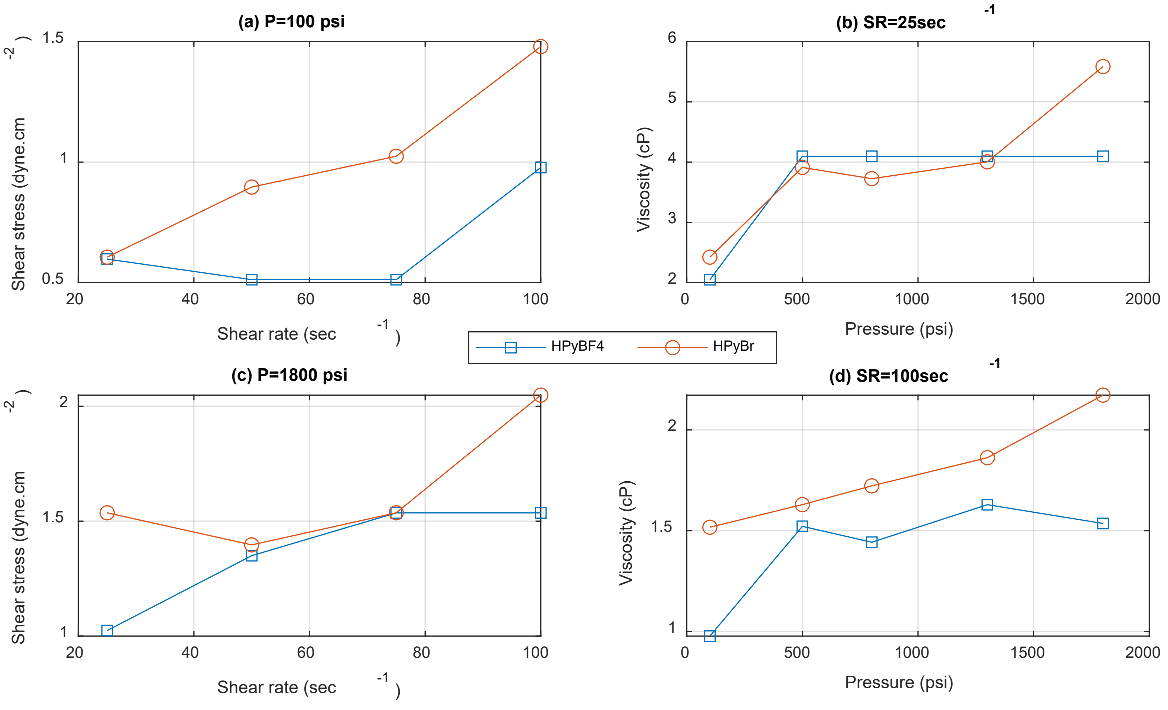

Figure 9: HPyBF4 and HPyBr Comparison under 380 °F at (a) 100 psi (b) 25 sec-1, (c) 1800 psi, and (d) 100 sec^{-1}.

3.3 Implication of ionic liquids in EGS application

Ionic liquids offer a potential benefit in their responsiveness to temperature changes, leading to a reduction in viscosity. This characteristic becomes particularly advantageous when utilizing these liquids for heat extraction in EGS. The ionic liquids examined in this study exhibit lower viscosity at higher temperatures and vice versa. Such behavior proves valuable as it allows the ionic liquid to flow more easily through narrower and hotter fractures compared to larger and colder fractures. Consequently, this enhances the efficiency of energy extraction. To support this claim, a theoretical pressure drop investigation is conducted using HPyBF4, HPyBr, and water for comparison. A smooth rectangular fracture with a hydraulic diameter of 7.11 mm was selected for the investigation. The pressure drop per unit length is calculated following Darcy–Weisbach equation (Rouse, 1946).

$$\frac{\Delta P}{L} = f_D \frac{\rho \times v^2}{2 \times D_h^2} \tag{1}$$

where ΔP is the pressure drop across the fracture, L is the fracture length, f_D is the Darcy friction factor, ρ is the fluid density, v is the average velocity, and D_h is the hydraulic diameter. For laminar flow (Re<2000), the Darcy friction factor is obtained using Equation 2.

$$f_D = \frac{64}{Re} \tag{2}$$

where Re is the Reynolds number, which is calculated as:

$$Re = \frac{\rho \times v^2 \times D_h}{\mu} \tag{3}$$

where μ is the fluid dynamic viscosity. For turbulent flow (Re>4000), the Darcy friction factor can be calculated using Kármán–Prandtl resistance equation in smooth pipes (Rouse, 1946).

$$\frac{1}{\sqrt{f_D}} = 1.930 \times \log\left(Re \times \sqrt{f_D}\right) - 0.537 \tag{4}$$

The input parameters for the pressure drop investigation are shown in Table 3 for different temperatures, where the viscosity of the ionic liquids is presented as a function of shear rate γ measured in sec^{-1} derived from HPHT rheology measurements.

Table 3. Pressure drops input parameters for water, HPyBr, and HPyBF4.

Temperature (°F)	Density (lb/gal)			Viscosity (cP)		
	Water	HPyBr	HPyBF4	Water	HPyBr	HPyBF4
68	8.33	10.85	9.68	1.00	720.34-0.231×γ	357.41-0.2075×γ
122	8.25	10.69	9.52	0.55	300.22-0.87×γ	89.415-0.1521×γ
176	8.11	10.53	9.36	0.35	224-1.188×γ	78.761-0.5586×γ

Figure 10(a-c) shows the pressure drop per unit length for water, HPyBr, and HPyBF4, respectively, for different flow rates in gallons per minute (GPM). Logically, higher pressure drops can be seen with higher flow rates and water shows a lower pressure drop per unit length compared to HPyBr and HPyBF4 due to lower dynamic viscosity. As temperature increases, the decrease in pressure drop per unit length is low due to the insignificant change in viscosity (Figure 10a). HPyBr has a higher viscosity and thus shows a higher pressure drop compared to water. The viscosity change due to temperature increase causes a significant change in pressure drop (Figure

10b). Similarly, HPyBF4 shows a significant reduction in pressure drop as a result of increasing temperature (Figure 10b).

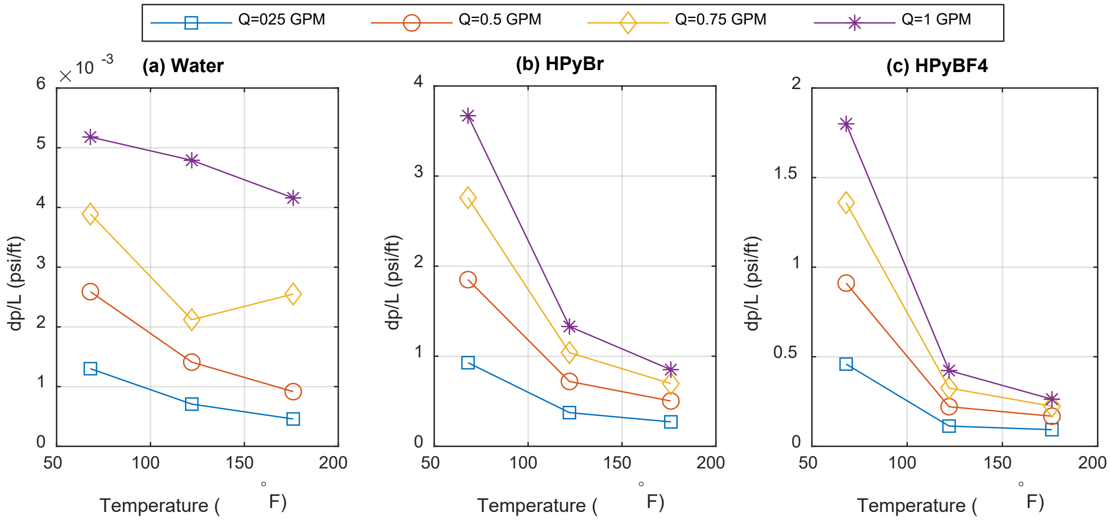

Figure 10: Pressure drop per unit length for (a) water, (b) HPyBr, and (c) HPyBF4.

The pressure drop behavior of the ionic liquids suggests that the fluid will be less resistant to flow through higher temperature fractures due to the significant change in viscosity. Such behavior can be used to stimulate smaller fractures with higher temperatures for efficient heat extraction and reducing short-circuiting.

As a comparison between the ionic liquids and water, the pressure drop reduction relative to water for 1 GPM due to temperature increases. Table 4 shows the change in pressure drop and relative reduction compared to water for the two ionic liquids. The reduction in pressure drop relative to water for HPyBr is higher than HPyBF4, where higher reduction indicates the ability to flow through higher temperature fractures.

Table 4. Change in pressure drop due to temperature change of HPyBr and HPyBF4 relative to water.

Temp. (°F)	**Pressure drops (psi/ft)**			**Change due to temperature**			**Frictional pressure loss reduction ratio**	
	Water	HPyBr	HPyBF4	Water	HPyBr	HPyBF4	HPyBr	HPyBF4
68	5.18E-03	3.67E+00	1.80E+00					
122	4.79E-03	1.33E+00	4.23E-01	8%	64%	54%	8.37	7.03
176	4.16E-03	8.51E-01	2.63E-01	20%	77%	71%	3.90	3.62

The results suggest that these ILs tend to flow more readily through smaller fracture systems with higher temperatures, rather than the larger ones with lower temperatures. This flow diversion is a gradual equilibrium process as the temperature in larger fractures starts decreasing over an extended period. An experimental fluid flow investigation in fracture networks will be necessary to verify the predicted behavior under varying temperatures.

4. Conclusion

The HPyBF4 and HPyBr ionic liquids were synthesized in the lab and their rheological properties were investigated using a HPHT rheometer. A power law model was fitted on the data to describe the behavior of the two ionic liquids under varying shear rates, pressure, and temperature. A theoretical pressure drop investigation was performed. The main conclusions of this work are:

- Both HPyBF4 and HPyBr show a reduction in shear stress and viscosity with increasing temperature. The shear stress response and viscosity of HPyBF4 and HPyBr remain relatively constant for temperatures higher than 310 °F. It is seen that the HPyBr in general shows higher viscosity compared to HPyBF4.
- Both ionic liquids show deviation from Newtonian fluid behavior with both displaying shear thinning characteristics. It is seen that the flow behavior index “n” decrease as the temperature increase.
- The viscosity values of HPyBF4 and HPyBr remain low at a constant temperature of 380 °F and are unaffected by changes in pressure.
- Ionic liquids exhibit greater pressure drop reduction relative to water with increasing temperature, which can be used to control short-circuiting in enhanced geothermal systems.

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